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SYSTEMATIC CONTROL OF NONMETALLIC MATERIALS FOR IMPROVED FIRE SAFETY

A REPORT

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

NASA SP-5109

SYSTEMATIC CONTROL OF NONMETALLIC MATERIALS FOR IMPROVED FIRE SAFETY

A REPORT

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CHAPTER 1

Introduction

Making a product or an area fire-safe is a complex problem, with many interactive variables. Flammable nonmetallic materials, ignition sources, oxygen-rich atmospheres, fire detection, and fire extinguishment are some of them. A systematic approach to this complex problem is presented in this report.

The elements of a systematic fire safety program are summarized in table 1, and consist of fire safety criteria, design considerations, testing of materials, development of nonmetallic materials, nonmetallic materials information systems, design reviews, and change control.

The system described in this report was developed for the Apollo spacecraft, and is not, for example, directly applicable to house construction or television set production. The system can, however, be tailored to many industrial, commercial, and military activities.

FIRE SAFETY CRITERIA

The first step in the development of a safe product or environment is the establishment of realistic criteria to govern the product design and development activities. To be effective, the criteria must be issued by management, with a full awareness of the overall program implications.

Realistic criteria involve the complexity of the product and environment, and the manner in which the product will be used. Criteria are needed for flame propagation, offgassing, and effect of fire on critical equipment.

Acknowledging that, in spite of all the efforts expended to make a product or environment safe, fire could still erupt, a fundamental criterion should be that the product or environment be fail-safe under the worst possible conditions.

DESIGNING FOR FIRE SAFETY

During the design of a product or environment, several important measures must be taken to assure that fire safety is properly considered. Many variables can be controlled during design, such as materials choice, location of components, protection of materials, and isolation of ignition sources; trade-offs are required to optimize these variables. Several of these measures are examined later in this report.

TESTING TO VERIFY DESIGN ADEQUACY

A comprehensive test program is essential. Although much can be done to optimize fire safety during design, test requirements must be developed to demonstrate the validity of the analyses and design.

A three-phase test program is depicted in figures 1a and 1b, and is described in this report. The program includes screening tests for basic nonmetallic materials such as fabrics, films, and foams; tests for equipment made of these basic nonmetallic materials; and flammability tests for a full-scale replica of the product. These tests were conducted during the design and development of the Apollo spacecraft, and subsequent to development, tests were conducted only as required to validate design changes.

NONMETALLIC MATERIALS DEVELOPMENT PROGRAM

A continuing developmental program of nonmetallic materials is an important aspect of product improvement. As part of the program, a constant search must be made for new and improved nonmetallic materials.

New chemical formulations and compounding methods that improve the flammability characteristics of nonmetallic materials without impairing their functional characteristics will evolve as suppliers of these materials are confronted with stringent requirements by the users.

TABLE 1.–*Elements of a Fire Safety Program*

Element	Subelement	Considerations
Fire safety criteria	Fire	Fireproof Fail-safe
	Offgassing	Critical equipment Propagation Toxicity
Design considerations	Hazards analysis	Worst-case
	Nonmetallic materials	Selection Location Protection
	Ignition sources	Protection/isolation Elimination
	Environment	Confined spaces Oxygen/air Closed ecological
	Fire/smoke detection Fire extinguishment Fire survival	Fire/smoke, automatic detection Oxygen/air Hyperbaric/hypobaric Procedures Smoke masks/egress
Testing of materials	Test requirements	Components/mockup
	Screening tests Component tests Flammability acceptance tests	Flammability/offgassing Flammability Flammability/offgassing
Materials development	Flammability Offgassing	New materials Improved materials
Materials information systems	Test data Materials usage information	Flammability/offgassing Use of nonmetallic materials
Design reviews	Preliminary Critical First article	Specifications Materials control plan Waivers and deviations
Change control	Design base line	Specification changes

NONMETALLIC MATERIALS INFORMATION SYSTEM

An essential element of a control program for nonmetallic materials is accurate and timely information. Designers need data on the flammability and offgassing of nonmetallic materials, program managers need information on the usage of nonmetallic materials, and safety engineers and materials specialists need information on their quantity and location in order to analyze hazards and devise tests. The need for information is especially important in the development of hardware, where changes are made continually. Information systems for these materials can be used advantageously by commercial organizations, such as aircraft manufacturers, airlines, and suppliers of aircraft equipment. The information system should provide both test data and usage information.

Test Data

The nonmetallic materials information system should provide data on the flame propagation rate, flash point, and fire point and offgassing characteristics (carbon monoxide, total organics, odor, and potentially toxic products). When several different agencies are involved in the testing of nonmetallic materials, a central data bank precludes duplicate testing. Accumulated test data is provided to contractors by MSC.

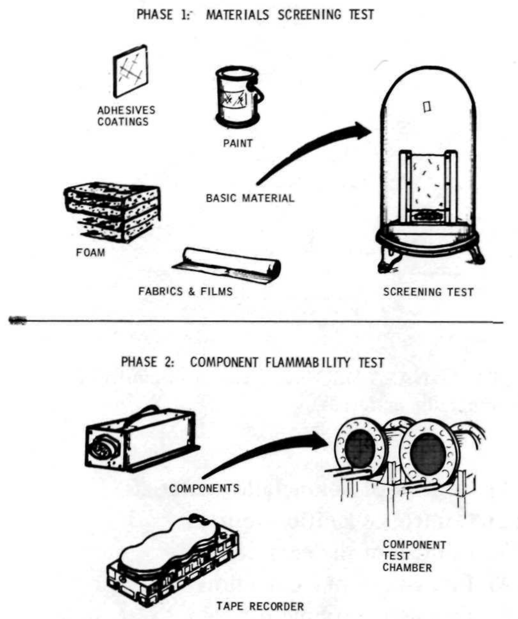

FIGURE 1a.–Three-phase test program–first two phases.

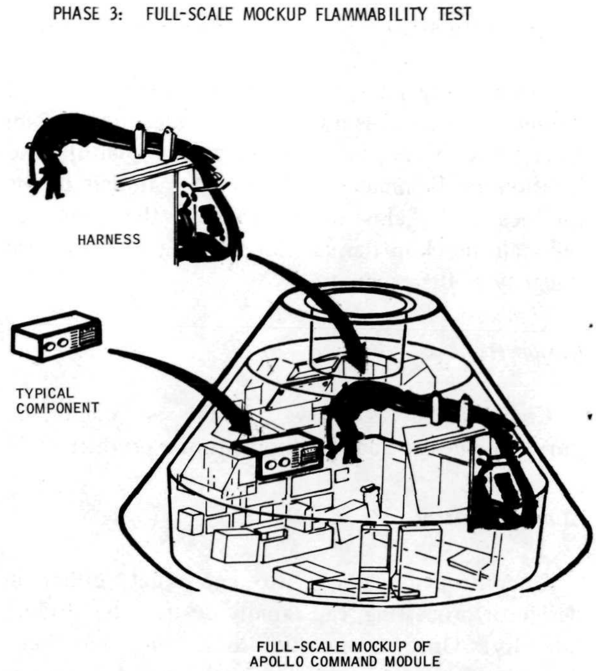

FIGURE 1b.–Three-phase test program–final phase.

TABLE 2.–*MSC Systems Engineering Approach to Fire Safety*

System element	Ideal conditions	Apollo spacecraft program: Solution	Apollo spacecraft program: Control method	Industrial/ commercial applications
Nonmetallic materials	All nonmetallic materials nonflammable and nontoxic	Flammable materials minimized, isolated, protected	Configuration management, materials information system, design reviews	Materials development, materials testing, test data, mockup tests, analyses
Ignition sources	No ignition sources where flammable materials are used	Ignition sources minimized, isolated, protected	Design, analyses, test	Removal/isolation, protection
Environment	Environment will not support combustion (inert)	60/40 oxygen/nitrogen used during prelaunch operations to reduce hazard	Prelaunch procedures	Inerting, mixed gas, venting
Fire/smoke detection Fire extinguishment Fire survival	Not required if any of the above is satisfied; otherwise, automatic detection of incipient fires, automatic alarms and extinguishment	Astronauts serve as detectors; hand-held fire extinguishers, smoke masks, and means for rapid egress provided	Astronaut and ground-crew training	Detection systems, alarms, sprinkler systems, escape provisions, foam systems
Program Management	Minimal	Implement flammability program	Materials control plan, design reviews, change control	Hazards analyses, product improvement, criteria

Usage Information

The information system should include data on all nonmetallic materials used. This provides the program manager with vital information on the quantity and location of flammable nonmetallic materials in the product and helps in determining the need for full-scale mockup flammability testing to verify the integrity of the product.

Design Reviews

Comprehensive reviews should be conducted during the design and development of a product.

Change Control

Uncontrolled changes to a product, either in design or processing, can rapidly destroy the product integrity. Once a product base line has been determined, a system should be established to control all changes, assuring that there is no degradation in the safety or reliability of the product.

MSC SYSTEM

Table 2 shows the systems approach developed, and how it can be applied to industrial and commercial operations. The approach has these elements:

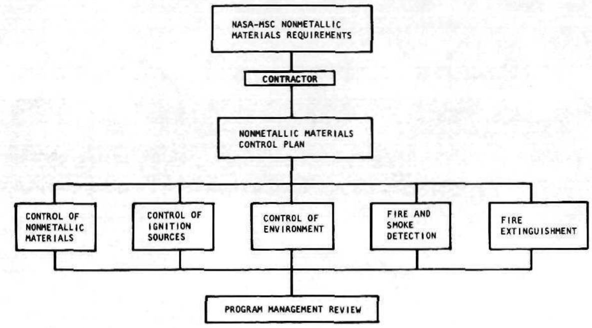

FIGURE 2.–NASA-MSC management of control program for nonmetallic materials.

(1) Control of nonmetallic materials
(2) Control of ignition sources
(3) Control of the environment
(4) Fire and smoke detection
(5) Fire extinguishment
(6) Program management

Manned Spacecraft Center established the basic requirements for the control of nonmetallic materials, and imposed them on the spacecraft contractors. The basic elements of the control program are shown in figure 2.

The spacecraft contractors identified the hazardous nonmetallic materials, which were isolated to assure that extensive usage and exposure of these materials would not cause them to ignite and propagate flame.

CHAPTER 2

Designing for Fire Safety

The most effective fire safety measures are those taken early in the design of a product, whether it be an aircraft, a television set, or a building. The designer is able to specify the types of nonmetallic materials and their placement with respect to potential ignition sources. Throughout the design process, trade-offs must be made between ideal fire safety measures and other considerations such as cost, weight, and, in many cases, aesthetics. This is "optimization," or the best possible compromise for each requirement.

FIRE SAFETY CONSIDERATIONS

To design a fire safe product, the designer must be familiar with the conditions under which the product is to be used. He must also be acquainted with potential hazards under the most severe usage that can reasonably be expected. In many cases, the designer is concerned with abuse of the product, and not merely normal usage. Broadly speaking, the main fire safety considerations are:

(1) Potential ignition sources
(2) Flammable nonmetallic materials
(3) The environment
(4) Fire detection
(5) Fire extinguishment
(6) Fire survival

Ignition Sources

Ideally, there would be no ignition sources. Realistically, the designer must contend with ignition sources within the product, as well as from external sources. When the designer knows what these potential ignition sources are, and where they are located, he can isolate his product from the potential ignition source or provide appropriate protection.

Flammable Nonmetallic Materials

The designer should specify nonflammable materials wherever practicable. Otherwise, he should select the least flammable material available. To do this, he must have data that include flammability and offgassing characteristics. When data are not available, or the data show unacceptable flammability characteristics, the designer must protect the flammable nonmetallic materials with nonflammable or less flammable ones.

The Environment

Two aspects of the environment concern the designer. The first is the atmosphere in which his product is to function; in most cases, the design atmosphere is air, while in others, it may be the more hazardous oxygen-rich atmospheres found in hyperbaric operating rooms and decompression chambers. The second environmental concern is the proximity of other flammable nonmetallic materials.

Coordination of Design Activities

In a complex design program where many designers are at work, each in his own special area, the coordination of their activities to produce an integrated design for fire safety is often extremely difficult. To assure that nonmetallic materials are evaluated properly, a comprehensive control program should be established with periodic design reviews. Control of nonmetallic materials must be considered jointly with other design measures such as control of ignition sources.

On long-duration programs, one aspect of the design is often completed before others are defined. This often results in redesign, which is costly, or in

compromises that may be costly and inefficient. Inherent in an integrated design effort are the economies that are possible by minimizing test requirements, and the opportunities to use lower cost nonmetallic materials.

When the designer is free to specify where his product is to be located with respect to other components, he can be aided materially by the fabrication of a full-scale mockup of the area. In a mockup, wire routing and component placement can be simulated, and rearrangements made.

Fire detection, extinguishment, and escape provisions are required when fire is possible, in spite of all other preventive measures employed.

ANALYSIS OF HAZARDS

Before a designer can start his task, he must carefully analyze how his product is to function, and any and all attendant hazards. In each case, there are varying degrees of risk. In confined spaces, such as submarines and decompression chambers, offgassing of nonmetallic materials is a significant potential hazard; in well-ventilated spaces, however, offgassing is usually not a problem.

The analysis of hazards should identify the most severe conditions under which the product must function throughout its useful life, including degradation and wear and tear. This is frequently referred to as "worst-case."

Another objective is to identify any and all equipment critical to human safety. The Apollo's guidance and navigation equipment, for example, is critical to the safe reentry of the spacecraft, and special fire safety measures are provided. As a backup for fail-safe design, a stabilization and control system is used.

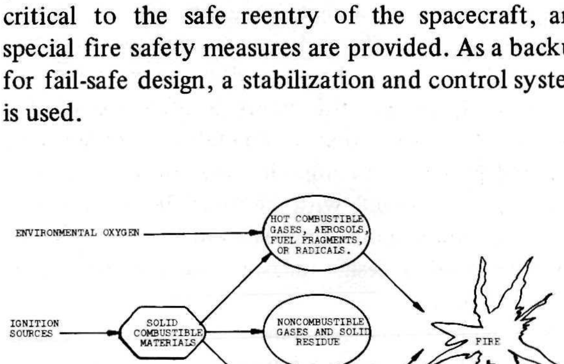

FIGURE 3.–Ignition of solid combustible materials.

IGNITION OF SOLID COMBUSTIBLE MATERIALS

Ignition may be defined as a process in which energy transfer is sufficient to cause rapid chemical reaction between an oxidizer and a combustible material or its volatilized products. Organic nonmetallic materials such as wood, plastic, and rubber, when subjected to a heat source such as electric spark or arc, hot wire, or direct flame, volatilize and decompose into chemical fragments or free radicals and gases. Basically, it is the rapid reaction of these products with oxygen that results in combustion.

The ignition of combustible materials such as char-forming coal, wood, plastics, and rubber is depicted in figure 3. The products are (1) combustible gases, aerosols, fuel-fragments, or radicals; (2) noncombustible gases and solid residue; and (3) combustible carbonaceous residue (char).

Other nonmetallic materials, such as cellulose nitrate and candle wax, melt, vaporize, or sublime, without charring. These materials have only a gas phase reaction with oxygen during ignition.

Factors Affecting Ignition

The ease of ignition of nonmetallic materials varies considerably. Firebrick, which is normally considered nonflammable, can be made to burn in fluorine gas. Extremely flammable nonmetallic materials such as nitrocellulose and ammonium nitrate contain a "built-in" oxidizer, and need no additional oxygen; these materials present the danger of autoignition in bulk storage. Some materials become extremely sensitive to ignition in the form of dusts and powders, often igniting spontaneously in air.

Ease of ignition depends on the interaction of material, oxidizer, and the energy source. Quantity, mass/area ratio of the material, rate, and type of initiating energy, such as electrical, mechanical, heat, light, and chemical, are important. Unless sufficient energy is transferred to a material (solid, gas, or liquid) when a sufficient quantity of oxygen is present for rapid chemical reaction, there can be no ignition.

Anything that interferes with the transport of oxygen and energy to the combustible material changes the probability of ignition of the material. Therefore, there are many ways to protect a combustible material from ignition. The ease of

ignition of materials is, then, not merely a characteristic of the flammable nature of the material itself, but more decisively, the protection from oxygen and/or ignition sources afforded.

Electrical Ignition

Electric energy is a common and difficult source of ignition to control. Short circuits resulting from damaged wire insulation, arcing caused by broken wires, or current overload in the conductor, may start a fire, but several measures may be used to minimize the risk of electrical ignition.

1. Circuit-protective devices.—Designers of electric circuitry frequently oversize circuit breakers to minimize the "nuisance" operation of these devices. Because circuit breakers cannot be relied on to open the circuit before dangerous overheating of the wiring occurs, circuit-breaker oversizing is a dangerous practice and should be employed only with other safety precautions. Solid-state circuit breakers have faster trip times than conventional circuit breakers. The designer can optimize circuit protection by specifying tighter tolerances on the circuit breaker trip time, and by sizing the circuit breaker for the minimum wire size.

2. Electric wire.—Wiring with insulation that is known to be nonflammable in the design environment should be specified. Several insulating materials were found unacceptable in the oxygen-rich atmosphere of the Apollo spacecraft, because they constitute a flame propagation path.

Many fires can be traced to short-circuits or grounds in wiring, which were caused by damaged insulation. To preclude the use of wire with damaged insulation in manned spaceflight equipment, MSC requires the wire manufacturer and/or the wire user to test every foot of wire by either a wet or dry dielectric test. Harnesses fabricated with this wire must also be tested prior to installation. A final dielectric test of the installed harness should be conducted prior to the connection of the harness to sensitive electronic equipment, to preclude damage to the equipment.

Throughout manufacturing, the wire user should apply stringent quality control to preclude wire damage. Also, protective devices should be used while the harnesses are in fabrication, and during their transport and installation.

3. Protection of wiring after installation.—Designers should provide protection for exposed wiring wherever analysis shows that the wiring can be damaged during its service life by personnel, by chafing or strain, or by impact of other objects. In the Apollo spacecraft, considerable wiring is exposed in the cabin, and is susceptible to damage by falling objects or technicians prior to launch, and by the flight crew after launch. The spacecraft contractors designed and installed fire-resistant protective covers over all harnesses that were considered susceptible to damage. A metal cable tray, which is used in the command module, was designed in removable sections, to facilitate inspection and wiring changes (fig. 4).

Another protection technique employed by MSC is the use of Teflon (TFE) film, wrapped around the wire harnesses.

4. Protection of electrical components.—Electrical systems commonly contain flammable components, such as the plastic housings for circuit breakers and switches. Ignition of these components, due to current overload or other causes, could ignite flammable nonmetallic materials.

Wherever possible, these components should be made of nonflammable materials. When flammable components must be used, several protective techniques will minimize the risk of their ignition.

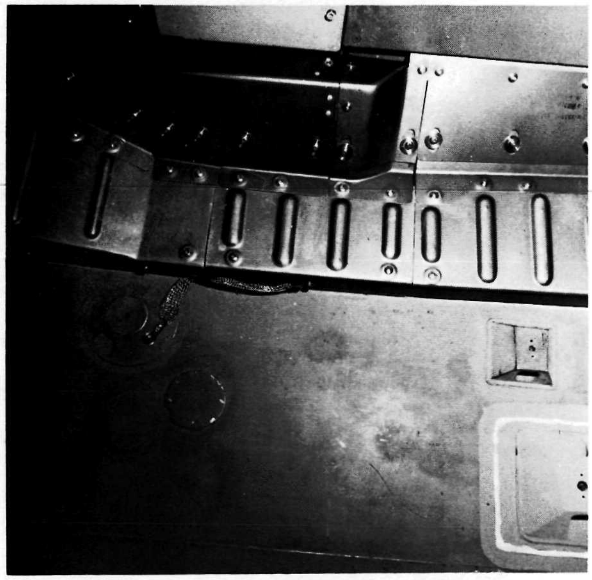

FIGURE 4.—View of cable trays used in the Apollo command module to protect electric wiring.

Figure 5 shows a group of circuit breakers, used in the Apollo spacecraft, individually encased in sleeves of a nonflammable glass-fabric composite. This arrangement isolates each component and protects it against fire in adjacent materials.

Another effective technique consists of wrapping Beta glass fabric around electric connectors (fig. 6).

5. *Protective coatings.*—Several fire-resistant coatings are available for protecting electrical components. The back side of the Apollo command module instrument panel, with a dense accumulation of switches, wire harnesses, instruments, and other electrical components is shown in figure 7. Several of these components are coated to prevent arc-over and short-circuits. Some of these coating materials are discussed in Chapter 4.

6. *Ignition by falling or dripping flaming material.*—An easily overlooked hazard is flaming particles that fall or drip onto flammable materials. This possibility becomes readily apparent with a full-scale mockup. Lacking a mockup, the designer must resort to analysis and review of designs of adjacent and overhead areas to evaluate the risk.

An example of this problem occurred in the full-scale mockup flammability test of the Apollo spacecraft, in which the flaming molten particles from electric wire splices dripped onto a polycarbonate helmet. In this case, the offending material was replaced with another less flammable and nondripping material.

7. *Electrostatic ignition.*—When two dissimilar materials contact each other, there is a transfer of energy in the form of flow of charge (electrons). Materials that permit the flow of electrons are classified as conductors. When moved apart, contact

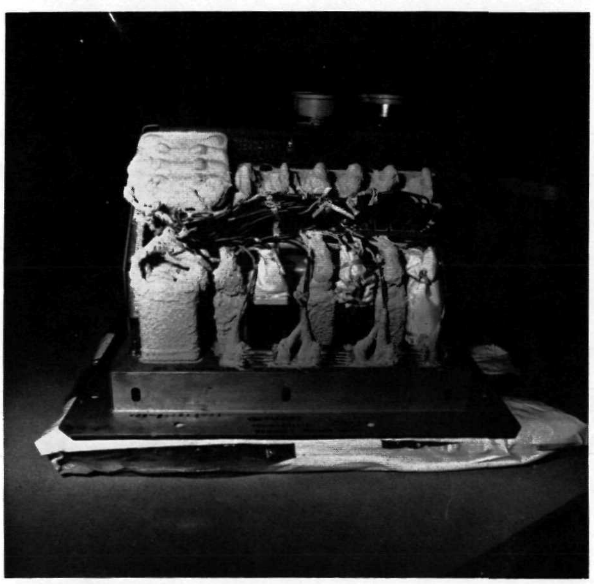

FIGURE 5.—Cluster of circuit breakers. (Each circuit breaker is encased in a sleeve of glass fabric.)

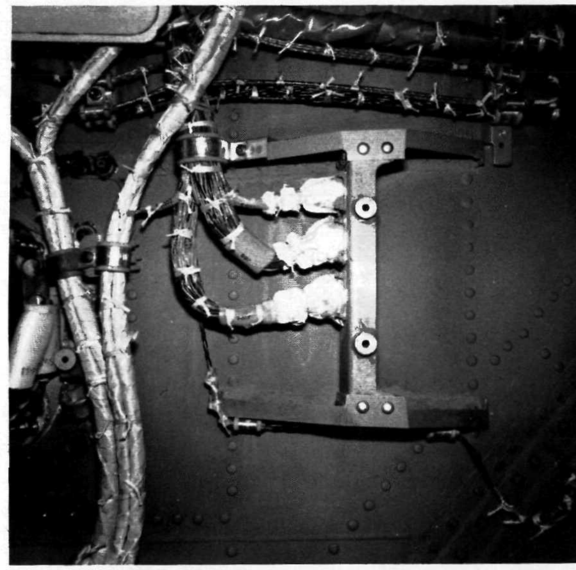

FIGURE 6.—Connectors on wiring harness. (Beta fabric is wrapped around connectors for fire protection.)

FIGURE 7.—Rear view of Apollo command module instrument panel. (Electrical components are covered with a fire resistant coating.)

surface charges are conducted away through the mass of the conductors. When one of the materials opposes the flow of charges, however, the charge remains on the surface of the nonconductor when the materials are separated. Thus, contact and separation will generate static electric charge or static electricity when a conductor and a nonconductor, or two different nonconductors are parted. Depending on the dielectric properties and effectiveness of surface contact, static charges produced by contact and separation of materials may be more than sufficient to provide a source of ignition for flammable materials.

The production of static electricity by contact of a space-suited man with the spacecraft was studied by rubbing the suit with various materials and measuring the voltage produced. Approximately 2 mJ of electric energy was accumulated by the test subject. This is based on the maximum measured capacitance of the man of approximately 200 $\mu\mu$F; the maximum electrostatic voltage observed was 4300 V over a wide range of conditions. In a spark, this amount of electrostatic energy is sufficient to ignite combustible gas vapors and mists, but not likely to ignite solid nonmetallic materials.

The danger of electrostatic ignition exists in hospital operating rooms, grain elevators, mines, food-processing plants and in industrial plants manufacturing explosives, propellants, hydrocarbons, and similar materials. In hospitals, static electricity, created by handling the breathing bag, has been known to ignite mixtures of oxygen and anesthetics such as cyclopropane, divinyl, and diethyl ether. The airborne organic dusts in grain elevators, food-processing plants, and many industrial plants are notably susceptible to fire started by static electricity.

Protection against electrostatic ignition consists primarily of assuring that the materials that will accept an electric charge are properly grounded. Designers should evaluate all materials for this phenomenon, and make sure that design features are incorporated to dissipate any accumulation of charge, especially when these components are used in the presence of combustible vapors or dusts. Ground straps should be kept short and connected close to the source of the charge. In some instances, antistatic agents can be used to change the dielectric properties of the materials.

8. Ignition induced by chemical reaction.– Another common mode of ignition is chemical reaction. For instance, hydrazine and nitrogen tetroxide are hypergolic, which simply means that they react with each other to cause ignition. Of the many modes of chemical ignition, the following is an example of a problem studied by MSC.

When a water/glycol solution comes in contact with current-carrying, silver-covered wire, a chemical reaction causes the silver to oxidize, and the glycol to dehydrate and decompose into ethylene oxide gas. The ethylene oxide reacts with hydrogen generated by electrolysis, and produces ethylene gas, which is combustible in air. This reaction can be prevented by adding 2000 to 5000 ppm of benzotriazole to the water/glycol solution. This mode of ignition was investigated because water/glycol solution and silver-covered wires are used in the Apollo spacecraft. Although water/glycol mixtures are used extensively as antifreeze and deicing solutions in automobiles, aircraft, and other machinery, the combination of water/glycol and silver-covered wires is not common. The substitution of nickel-covered wires prevents such a reaction.

SELECTION OF NONMETALLIC MATERIALS

If all the nonmetallic materials required for a given application were fire resistant, the task of selecting the materials would be a matter of cost, aesthetics, or other considerations. Since this is not so, some method of controlling the use of flammable materials must be employed. MSC developed a systematic method of selecting materials by categorization.

Categorization is a method of selecting nonmetallic materials in accordance with the requirements of the environment in which the materials are to be used, the quantity of materials involved, and their flammability characteristics.

The environment includes physical and atmospheric conditions. For example, if the atmosphere is rich in oxygen, as in certain areas in hospitals and in decompression chambers, the fire hazard is greater than in air. Thus, the materials used in these areas must be essentially nonflammable. An exception can be made if the quantity of material involved is relatively small, and certain flammability requirements are satisfied. Other considerations include potential ignition sources and possible flame propagation.

The concept of categorization requires that every

area where nonmetallic materials are used be studied for the degree of risk that exists in each of these areas, whether in the home, a hospital, or any other environment. The selection of materials must be commensurate with the degree of risk. In the hospital, for example, the use of pure oxygen presents a more severe flammability problem than is normally found in the home. Those areas of a hospital where pure oxygen is used have a higher risk factor, and the selection of nonmetallic materials for use in these oxygen-rich environments is much more critical. If oxygen-rich environments are established as the most hazardous (in some cases, fluorine would be even more hazardous than oxygen), criteria for the selection of nonmetallic materials can be determined.

This process of categorization for the Apollo spacecraft is depicted in figure 8. The spacecraft is first considered within three broad categories of nonmetallic materials: (1) those used in high-pressure oxygen systems, (2) those in the crew bay, and (3) those outside of the crew bay. In each of these categories, there are significant differences. In the crew bay, for example, the pure-oxygen atmosphere is a far more hazardous environment than the areas outside of the cabin, where there is no atmosphere while in space. The acceptance criteria for the nonmetallic materials used in these two areas are quite different. Similarly, special consideration is required for the materials used in high-pressure oxygen systems, either in the crew bay or outside.

As shown in figure 8, there is a distinction between the nonmetallic materials used in the crew bay during flight and during ground tests, because the flammability requirements are less stringent for

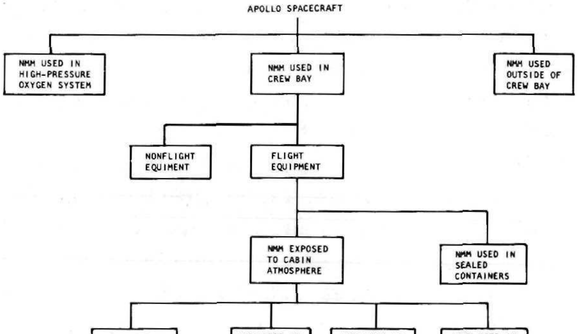

FIGURE 8.–Apollo spacecraft nonmetallic materials categorization (NMM = nonmetallic materials).

nonflight materials. When the nonflight equipment is used during a ground test in which the cabin is sealed, pressurized with oxygen, and personnel are in the cabin, the materials used in the nonflight equipment must meet the flammability requirements of flight equipment.

For flight equipment, figure 8 shows two new breakouts: (1) nonmetallic materials exposed to the atmosphere and (2) nonmetallic materials used in sealed containers. The flammability requirements in these two cases are significantly different.

The last breakout shown in figure 8 shows four categories for the use of nonmetallic materials; each has special test requirements and acceptance criteria.

The most significant group of nonmetallic materials is that where large quantities are involved. For example, the space suit outer materials and the paint used in the cabin are considered large quantities; the materials must be nonflammable, or if ignited, must be self-extinguishing within some predetermined distance in any direction from the ignition source. In the Apollo spacecraft, burning is restricted to 3 in.; all visible flame has to cease within 180 sec after ignition; and all smoldering (afterglow) has to cease within 600 sec. No dripping, sputtering, or sparking of the material that results in the transfer of burning mass is permissible. Where large quantities of nonmetallic materials are needed but do not meet the above requirements, and no acceptable substitute is available, they must be protected by materials that satisfy the requirements.

Nonmetallic materials in small items, such as knobs and instrument dial faces, may be used, even though tests show that they will sustain combustion. It must be demonstrated, however, that they will not contribute to flame propagation to adjacent equipment or materials.

A category of nonmetallic materials in vented containers was established for stowage, electric junction boxes, food warmers, and cameras. The containers may or may not contain an ignition source, and they must not emit flame or burning materials through rupture or vents.

Nonmetallic materials used in the astronaut suit system is another category. It includes hoses, helmets, flexible joints, valve seats and seals, and the inner-garment materials. These materials must meet the same requirements as the large-quantity materials category discussed above, or must be protected by nonflammable materials.

Categorizing nonmetallic materials by usage groups can be adapted to many commercial activities as well. A good example is military and commercial aircraft, in which the crew compartment, passenger cabin, galleys, baggage compartments, and engine compartments are logical areas for evaluating the use of nonmetallic materials. Similar compartmentation is present in ships and submersibles. The concept can be extended readily to hospitals, hotels and motels, nursing and convalescent homes, and, in fact, even the private home or apartment; the principle is the same.

In selecting a nonmetallic material, the designer must consider both its flammability characteristics and the offgassing characteristics, including odor, carbon monoxide, total organics, and potentially toxic products. In many cases, the offgassed products are toxic and can be very harmful to man.

Most organic materials offgas to some extent, even at normal atmospheric conditions; many materials on the other hand do not offgas significantly except at elevated temperatures, reduced pressures, or a combination of both.

Offgassing is greatly affected by changes in temperature and pressure; raising the temperature increases the rate of offgassing by supplying energy for reaction and evaporation. This increase in temperature raises the average energy of the molecules, and increases the probability of their escape from the surface. Lowering the pressure will also increase the rate of offgassing by aiding evaporation, and by aiding the formation of a diffusion gradient within the material.

In the selection of materials for housewares, television sets, upholstery fabrics, paints, solvents, cleaning agents, and other applications, care must be taken to make certain that these materials do not offgas harmful products, especially if they are likely to be exposed to elevated temperatures in confined spaces.

Criteria for acceptance of nonmetallic materials in NASA programs evolved from the experiences of toxicologists in the U.S. Navy, NASA contractors, and within NASA.

PROTECTION OF FLAMMABLE NONMETALLIC MATERIALS

When the use of flammable nonmetallic materials is unavoidable and the quantity constitutes a fire hazard, the flammable material should be shielded from any potential ignition source with nonflammable material. The flammable material may be coated with any of several fire retardant coatings, wrapped or enclosed in fire resistant material, isolated, or protected by heat-sink techniques.

The simplest way to protect a structure from the effect of heat is to provide a resistance to the flow of heat from the heat source to the structure. Several classes of nonmetallic materials that provide this resistance are:

(1) Intumescent coatings, which have been in use for several years

(2) Fluorocarbon elastomers

(3) Lightweight plastic foams, which are relatively new.

Intumescent Coatings

Significant advances have been made in the use of intumescent coatings as fire retardants. Intumescence, which is the swelling or bubbling of a substance when exposed to heat, has been used for several years in surface coatings to protect fire-sensitive materials. A Halloween novelty item called *Pharoah's Serpent*, a cube of chemical that expands when ignited, is a form of intumescence. Another example is the college chemistry laboratory experiment in which sulfuric acid and sugar produce a large volume of low-density carbonaceous solid.

The principal drawback to the coatings used in the past was their inability to withstand the rigors of outdoor exposure. The advent of new polymers such as polybenzimidazoles, polythiazoles, polyphenoxazines, and polyquinoxalines, has made it possible to develop better char-forming materials for intumescent systems. At this point of development, these coatings should be used only in well-ventilated and unpopulated areas, because of the quantities of highly toxic sulfur dioxide released. Research is continuing, and the prospects for safe and effective fire-retardant coatings are promising.

Some suggested coating applications are: electric motor casings, equipment in fuel and chemical plants and tank farms, engine canopies, ventilator grids, and building exteriors.

Fluorocarbon Polymers

New compounds were produced to provide

fire-resistant coatings for the Apollo spacecraft and other applications. These compounds, copolymers of vinylidene fluoride and hexafluoropropene, are available commercially under the trade names of Viton and Fluorel. The use of these coatings on the Mobile Quarantine Facility (fig. 9), in which the Apollo astronauts were confined following their return from the Moon, is an example of MSC application. All wood and vinyl interior surfaces were coated with a fluorocarbon solution. A view of the lounge area, showing some of the surfaces that were coated, is shown in figure 10.

Lightweight Plastic Foams

Research on the chemistry of ablation for protection of spacecraft during atmospheric entry led to the development of this new class of fire-retardant materials by Ames Research Center. Foams were developed principally to protect aircraft structures and externally mounted fuel tanks from onboard fires in flight. Fire-retardant foams have been made from urethane, isocyanurate, and polybenzimidazole. The effectiveness of many fire-suppressant or extinguishing materials lies in the generation of a large quantity of gaseous products. For the most part, these gaseous products range from mildly to severely toxic, so the retardant materials should be used with caution.

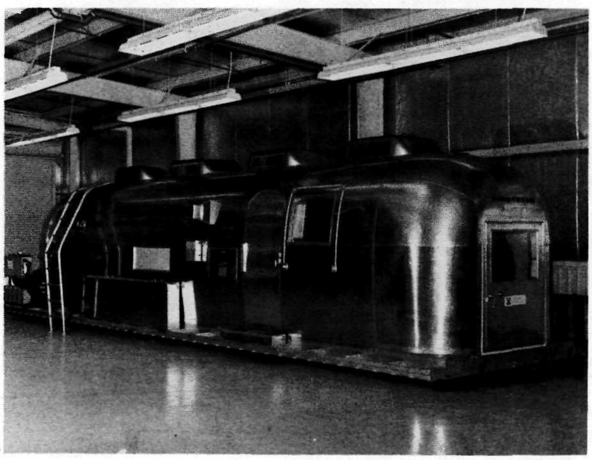

FIGURE 9.–Mobile Quarantine Facility. (Apollo astronauts were confined to this facility after their return from the Moon.)

FIGURE 10.–Interior view of the Mobile Quarantine Facility. (All interior surfaces of wood and vinyl were treated for fireproofing.)

Sleeves, Bags, Wrappings

The use of glass-fabric sleeves to protect flammable circuit-breaker housings was shown previously (fig. 5), as well as the use of glass-fabric bags to protect electric connectors (fig. 6). Another method of protecting flammable nonmetallic materials is to wrap them with nonflammable Teflon (TFE) film. When using wrap-around nonmetallic materials for fire protection, care must be taken to bind the material securely with nonflammable materials.

FIRE AND SMOKE DETECTION

The early detection of incipient fire or smoke is essential if fires are to be controlled. Selection of a fire detection system should be based on sensitivity, speed of response, and reliability, including freedom from false indications. Other factors to consider are size, weight, power requirements, ease of installation and maintenance, and compatibility with other materials and equipment.

Several detection systems have been in service in industrial plants for several years and are the basic systems being considered for commercial airliners.

In the confined space of the Apollo spacecraft, a detection system was not used. It was felt that the astronauts would be able to see the fire or smell the smoke, and bring the fire under control with a fire extinguisher.

In future space missions of longer duration, spacecraft will have larger internal areas than the Apollo requiring some method of fire and smoke detection, especially in unoccupied areas. A detection system is incorporated in the Skylab Orbital Workshop. Fire-detection systems are also used by MSC during manned tests in the large vacuum chambers.

FIRE EXTINGUISHMENT

The extinguishment of fire in air and oxygen-rich atmospheres, at pressures above atmospheric (hyperbaric) and below atmospheric (hypobaric), was investigated by MSC. The results of the investigation are summarized below and should be of interest to industrial, medical, and military organizations. Examples of hyperbaric facilities are: decompression chambers for deep sea divers, oceanographic chambers, submarines, and chambers for the treatment of dysbarism in medical centers. Hypobaric equipment includes the pressurized compartments of commercial and military aircraft, incubators for infants, and high-altitude test chambers.

MSC tested several gases, solids, and liquids; the effectiveness of these extinguishants is summarized in table 3. Several extinguishing agents widely used for fires in air were ineffective or even detrimental in the oxygen-rich test atmospheres, because they increased the burning rate. Water, aqueous gel, and water-based foam proved to be the most effective extinguishants for fires in oxygen-rich atmospheres.

Fire extinguishing agents for use in manned oxygen-rich environments must not (1) support combustion, (2) emit toxic or anesthetic products, (3) obstruct vision, or (4) be electrically conductive. A special hand-held fire extinguisher (fig. 11), with a water-based cellulose gel foam that was compounded specifically for the zero-gravity spacecraft environment, was used in the pure-oxygen hypobaric atmosphere of the Apollo.

Analysis of the fire hazard in the spacecraft disclosed that fire could erupt in areas such as the back side of the instrument panels. Therefore, the hand-held fire extinguisher was equipped with a flexible metal hose which could be inserted into special apertures in the panels to reach the otherwise inaccessible fire zones.

Inerting is the process of rendering an environment incapable of supporting combustion. Some of the inerting agents that have been used effectively are water vapor, nitrogen gas, helium gas, and halocarbon gases. The Bureau of Mines conducted a study of spillage of Aerozine-50, and means of inerting the atmosphere in the vicinity of the spillage. The

TABLE 3.—*Rating of Extinguishment Agents*

[Polyurethane-foam fire in oxygen (5 to 16.2 psia)]

Agent	Effectiveness
Gases	
Halon 1301	Intensifies burning
Helium	Intensifies burning
Nitrogen[a]	Intensifies burning
Argon	Intensifies burning
Carbon dioxide[a]	Intensifies burning
Solids	
Sodium bicarbonate	Ineffective
Potassium bicarbonate	Ineffective
Liquids	
Water	Good
Foam	Good
Ethylene glycol solution	Poor
Gel solution[b]	Excellent
Vent	
Pump down to 0.12 psia in 2 min	Ineffective

[a]It is theorized that these gases intensify burning because they transport oxygen to the flame.

[b]Water containing gel (0.25 percent), 300 to 350 cP.

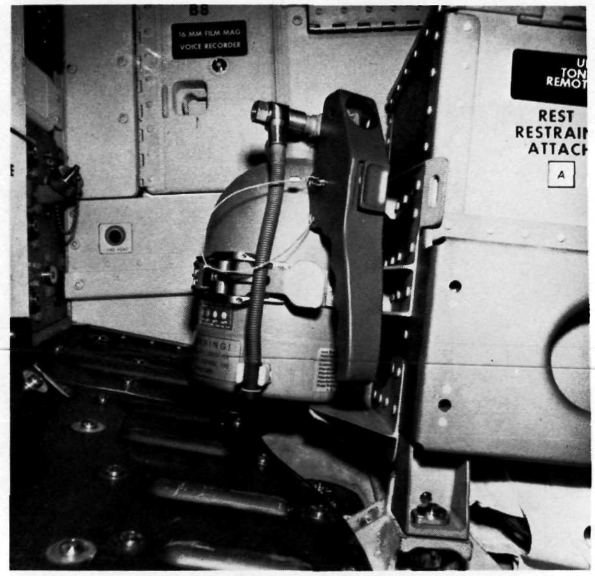

FIGURE 11.—Apollo hand-held fire extinguisher and fire port.

principles are applicable wherever volatile chemicals are processed or used. The study shows that 2 parts of water by weight to 1 part of Aerozine-50 will prevent ignition in air. Where large quantities of water cannot be used, halocarbon (Halon 1301), approximately 7 percent by volume, may be used.

FIRE SURVIVAL

The final and most important consideration in a fire safety program is the ability of personnel to survive the fire. There are innumerable cases on record of fires in dance halls, theaters, lounges, convalescent homes, and aircraft, where the occupants were unable to escape or be rescued because of smoke, fire, or other deterrents.

Fire-survival provisions include emergency procedures and equipment, smoke-inhalation protection, and adequate means of rapid egress. The Apollo astronauts undergo a training program of emergency procedures, including the use of a smoke mask. A quick-opening hatch permits rapid egress from the command module in the event of a fire during manned operations on the launch pad.

In confined spaces, such as mines, aircraft, submarines, and chambers, gas masks can provide immediate breathing safety where egress may be delayed and emergency fire fighting is required.

CHAPTER 3

Testing of Nonmetallic Materials

When flammability and offgassing data are not available, nonmetallic materials and their applications must be tested under the most severe ignition and environmental conditions expected in their end use.

The approach is a three-phase program, starting with material screening tests, followed by tests of the component or assembly alone, and then in a simulation of its end use. This program has the obvious advantage of revealing unacceptable conditions in the earliest stages of development.

SCREENING TESTS

Samples of nonmetallic materials are tested for flammability and offgassing characteristics. The flammability tests determine the temperature at which these materials ignite in the test environments, and the rate at which they burn, once ignited. Offgassing tests determine the quantity and nature of the products released from the materials under reduced atmospheric pressures and elevated temperatures.

Flammability Screening Tests

To understand fully the flammability characteristics of nonmetallic materials, screening tests are required and are conducted to simulate the design conditions. One test is required to determine if the material will sustain combustion, and if so, the rate at which it burns; another to determine the flashpoint and firepoint of the material.

1. Test chamber.—The flammability test chamber must have sufficient volume for complete combustion of the sample without significant depletion of its oxygen. In special atmospheres, such as the 100-percent oxygen atmospheres used by MSC, provisions are required to evacuate the test chamber, then pressurize it with the required gas or gases. The MSC test chamber is shown in figure 12.

2. Test fixture.—Figure 13 shows a fixture used to support a material sample.

3. Sample preparation.—Films, foams, and fabrics are normally tested in the design condition and thickness. Samples used by MSC are 2½ by 5 in. Primers, coating materials, and paints are applied over a piece of material that closely represents its actual use in order that the effects of thickness and thermal conductivity of the substrate material can be evaluated.

4. Ignitor.—The ignitor must be representative of the most severe ignition mechanism anticipated for the particular materials and applications. For example, analysis of the nonmetallic materials used in the Apollo spacecraft disclosed that considerable silicone rubber is used as an electrical potting compound. It burns vigorously in the pure-oxygen atmosphere of the spacecraft, and, once ignited,

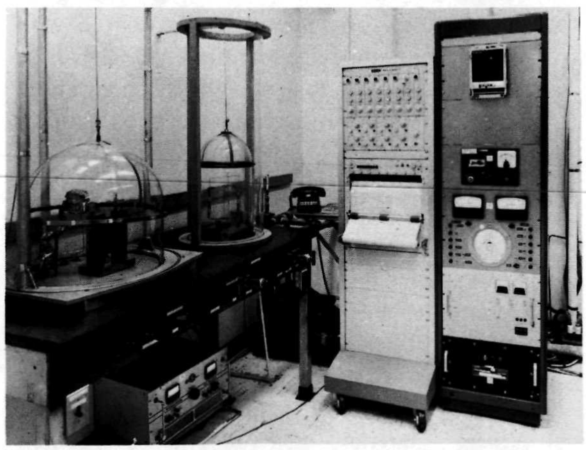

FIGURE 12.—Flammability test chamber and associated instrumentation.

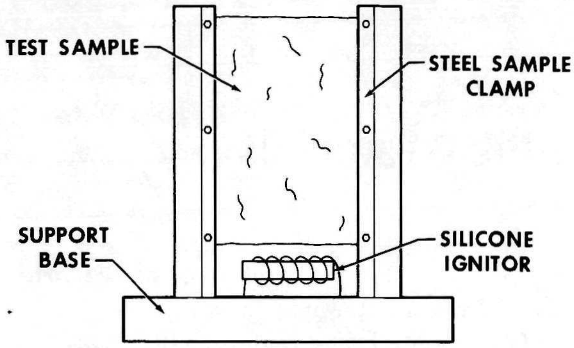

FIGURE 13.–Schematic of flame propagation test fixture. (Silicone rubber ignitor is shown at the bottom edge of the test sample.)

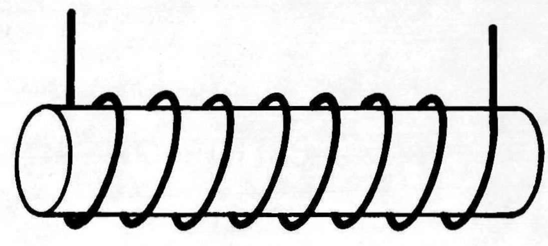

FIGURE 14.–Silicone-rubber ignitor.

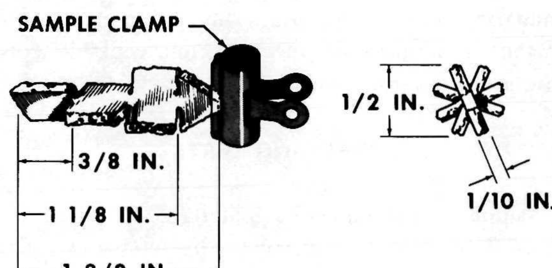

FIGURE 15.–Standard polycarbonate ignitor.

becomes an ignition source for other nonmetallic materials. This material was therefore established as the worst-case material, and was used as the standard ignitor for testing other nonmetallic materials.

The ignitor (fig. 14) burns for approximately 25 sec in pure oxygen. The burning time is a function of the ignitor geometry and the test environment. The silicone rubber ignitor is not practical for testing materials in air because of the large amount of smoke produced during combustion in air.

The silicone rod is ignited with a regulated energy source. This source consists of a nickel-chromium wire, 20 AWG, with a nominal resistivity of 0.7 ohms/ft, long enough to wind 6 to 8 turns around the length of the rod. The power supply to the wire provides sufficient amperage, controlled by means of a variable transformer, to ignite the silicone-rubber rod. Current to the wire is terminated upon ignition of the rod.

5. *Polycarbonate drip-ignition test.*–One of the potential ignition sources is the dripping of flaming molten particles onto other flammable nonmetallic materials. A special device is required to test materials for this condition. For MSC tests, polycarbonate was used as the most severe ignitor, because the molten material clings to whatever it contacts and continues to burn. Polycarbonate does not burn in air and the most severe material used in the anticipated environment should be selected for each application.

The prime consideration in designing the polycarbonate drip tester was to obtain repeatability in the size of the molten droplets. This was accomplished by establishing a uniform ignitor size, by notching the ignitor as shown in figure 15, and by attaching the ignitor mount to a low-speed vibrator that shakes the ignitor at 1-sec intervals. A schematic of the test device is shown in figure 16.

6. *Upward propagation test.*–This test is designed to identify nonmetallic materials that could promote the rapid spread of fire. It is the most severe flammability test conducted, due to the positioning of the ignitor. With the ignitor positioned at the bottom of the sample (fig. 13), the sample is exposed to energy transfer by convection and diffusion. Materials tested in this manner are considered acceptable if they do not ignite, or if they self-extinguish after ignition within a predetermined distance. Apollo spacecraft materials which ignited were restricted to a propagation of no more than 3 in. along the sample length.

7. *Downward propagation test.*–Nonmetallic materials that fail the upward propagation test are tested again, with the ignitor positioned at the top of the sample to determine the propagation rate. If the materials meet the established requirements, they may be used in certain restricted applications where they do not contribute to flame propagation. In this

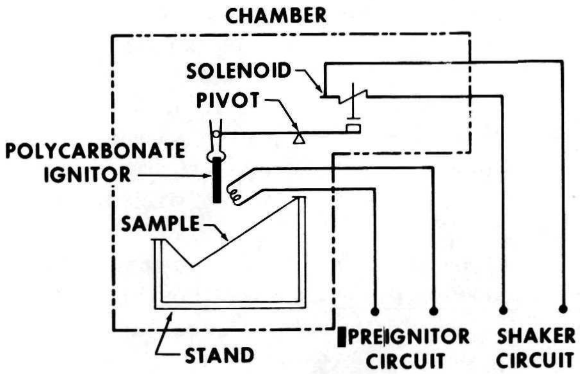

FIGURE 16.–Schematic of polycarbonate drip-ignition tester.

test, the flames rise away from the unburned material, which is not exposed to the convective effects of the flaming material. Flame propagation rate is measured, either by high-speed photography or by means of a thermocouple rake. Acceptance criteria must be established for each case, as part of the design process.

8. *Flashpoint and firepoint test.*–This test is used to determine the lowest temperatures at which a nonmetallic material emits a flammable gas or vapor that ignites in the presence of a spark. The ignition can be transient or sustained, according to the following definitions. The flashpoint is the lowest temperature at which a heated nonmetallic material will emit flammable vapors in such quantities that these vapors will result in a nonsustaining flash or flame when mixed with oxygen and exposed to an electric spark of a preselected energy level (usually 100 mJ at 10 000 V). The fire (ignition) point is the lowest temperature at which a heated nonmetallic material will emit sufficient flammable vapors to result in a self-sustaining fire when the vapors are mixed with oxygen and exposed to an electric spark of a preselected energy level (usually 100 mJ at 10 000 V).

To preclude the use of low flash- and fire-point materials, those materials that exhibit a visible flash at a temperature less than 400° F, or show evidence of charring, self-sustaining combustion, or other signs of pyrolysis at a temperature less than 450° F, are not acceptable for use in the Apollo crew bay areas.

The test equipment is shown in figure 17; it consists of a furnace, a test stand, needle electrodes with associated spark-producing equipment, and a vacuum chamber with equipment for supplying oxygen or a gas mixture. The apparatus heats a sample at a desired rate and exposes the offgassed volatiles to a spark of predetermined energy. The test is monitored visually by means of a prism on top of the furnace, or by the use of thermocouples or photocells mounted in the furnace.

9. *Short-circuit ignition test.*–A special test device (fig. 18) was developed by MSC to evaluate the effects of electric short-circuits on adjacent flammable nonmetallic materials. The device consists of an electrically isolated needle electrode and a stationary flat copper disk.

The needle electrode is scraped across the material to simulate the action of a broken electric wire, and the resulting arc is observed to determine whether it has sufficient energy to ignite the material. In this manner, the minimum current capable of igniting the material at any preestablished voltage can be determined. This test was designed to make certain that the cotton undergarments worn by the astronauts would be safe in the event that the electric wiring worn by them for communications and bioinstrumentation should cause an arc.

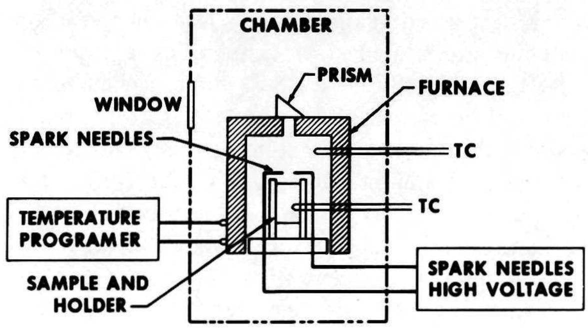

FIGURE 17.–Schematic of the tester for flashpoint and firepoint.

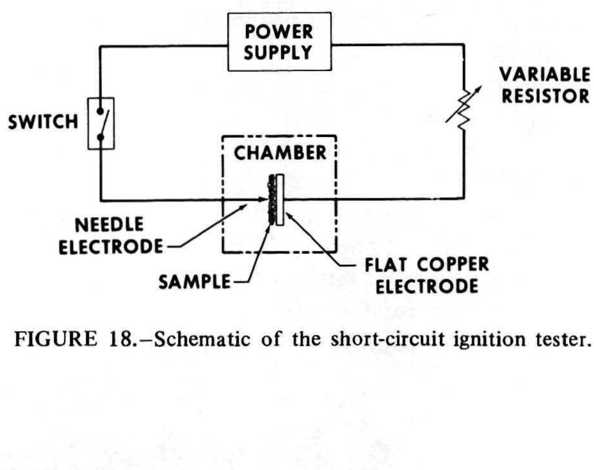

FIGURE 18.–Schematic of the short-circuit ignition tester.

This test could be used to simulate building or aircraft electrical systems and to evaluate the ignition characteristics of insulation and structural materials.

Offgassing Tests

It has been shown that when certain materials are exposed to elevated temperatures and/or reduced pressures, gaseous products are evolved. Some of these products are combustible, as was shown in the section on flammability tests. These offgassed products may be nauseating and/or hazardous (toxic) and may be present with or without combustion. Two tests have been developed to evaluate the quantity and nature of these products. Other tests were conducted with animals to determine the effects of the offgassed products, and based on the findings of these tests, criteria were established for the selection of nonmetallic materials. Interested readers are encouraged to examine the literature on this subject, some of which is listed in the bibliography at the end of this report.

1. Odor.—To preclude the use of nonmetallic materials that might offgas objectionable odors, a special test was developed. In this test, samples of the materials are heated to a temperature of approximately 155° F for at least 72 hr in a chamber. A panel of personnel with acute olfactory senses evaluate the test chamber atmosphere by comparison with other common odors. One of the concerns in this test is the safety of the panel members. It would be hazardous to subject the members to unknown gases of unknown concentrations. For this reason, the offgassed products are analyzed by gas chromatography and infrared scan before exposing the panel members to the gases. When the analysis shows that the total organics in the sample exceeds 240 ppm (by volume), or that toxic gases are present in detectable concentrations, the sample is not submitted to the panel for evaluation but is further analyzed medically for toxicity.

This test is particularly significant to manufacturers of consumer products such as shower curtains, plastic toys and similar articles, and upholstery fabrics.

2. Carbon monoxide and total organics.—In this test, the sample of nonmetallic material is placed in a container of oxygen at a pressure of 5 psia, then heated to a temperature of 150± 5° F for 72 hr. The oxygen in the container is then analyzed, by mass spectrometry, infrared spectrometry, and gas chromatography, for carbon monoxide and total organics.

For MSC programs, samples which offgas carbon monoxide in excess of 24 ppm by weight, or total organics in excess of 100 ppm by weight are rejected. These criteria are based on a medically acceptable risk level.

3. Other potentially toxic products.—Some potentially toxic products which should be checked when used in sufficient concentration and time duration are:

Hydrogen cyanide
Benzene
Xylene
Methyl ethyl ketone
Chloroform
Normal butanol
Dichloromethane
1,4 dioxane
Formaldehyde
Trichloroethylene
Hydrogen chloride
Ammonia
Hydrogen fluoride
Carbonyl fluoride
Silicon tetrafluoride

COMPONENT FLAMMABILITY TESTS

The initial selection and design of nonmetallic materials for various components comprise the necessary base line from which controls are used to minimize flammability characteristics. The component flammability tests consist of determining the combustion characteristics of a number of different nonmetallic materials that make up a functional assembly. These tests determine or verify the behavior of the component under the particular test condition. Some of the tests conducted by MSC are described below.

Testing Electric-Wire Insulation

This test is designed to screen flammable wire insulation, as well as accessory components such as heat-shrinkable tubing used on wire splices, lacing cord or spot ties, and cable clamps. It is performed by forcing current overload, up to the fusion point of the wire or component.

Testing Potting Compounds and Coatings

These tests simulate short circuits, dielectric breakdown of conductors, or terminal block failures. The test articles are subjected to current overload, up to the fusion point of the metallic elements of the components.

Testing Nonmetallic Materials in Unsealed Containers

This test is intended to determine the behavior of materials in containers such as electric junction boxes, food warmers, and cameras, and the effects of combustion of these materials on adjacent materials and equipment.

Two modes of ignition are used: (1) an internal ignitor for those containers that have such a source and (2) an external ignitor for containers with no internal ignitor. The internal ignitor used by MSC is the same as that described earlier in Screening Tests; it is positioned close to the material to be tested. The external ignitor consists of a flame source that is representative of the worst possible spacecraft fire, and is positioned outside the container opposite the most combustible material in the test article. Sufficient energy is thus provided by the ignition source to ignite the container or assure that it will not ignite in actual use. Analysis should validate the selection of the ignition source. The principal concern is to assure that the material inside the container, once ignited, does not become a source of ignition for other flammable materials outside the container.

Testing Nonmetallic Materials in Sealed Containers

Components installed in sealed containers should be tested to verify that the container will not rupture due to the built up pressure from an internal fire. The container may or may not have an internal ignition source. This test can also be used to verify that an internal fire does not impair the function of the component.

The materials in the container should be arranged as in the finished product. Worst-case arrangement of materials, that is, concentrations of materials in close proximity as well as those adjacent to high voltage/current sources should be used. In the case of containers with an internal ignition source such as electric wiring, ignition is tested by current overload of the electric wiring. This requires a power supply that can provide a large steady current, 10 percent above the nominal fusion current for the wire being tested.

Containers with no internal ignition source are treated as described for the testing of unsealed containers.

FLAMMABILITY ACCEPTANCE TESTS

Final verification of the utility of the fire safety measures designed into the product can best be obtained by preparing a full-size replica of the product, and observing the effects of fires from actual ignition sources, under worst-case conditions.

The objectives of this test are:

(1) Determine whether the fire will propagate
(2) Determine the degree of flame propagation
(3) Determine the magnitude of the fire
(4) Identify the nature of propagation paths

A full-scale mockup to verify the fire safety of a product can be used very effectively in building aircraft, ships, and buses. Where a mockup is not practicable, special analytical techniques can assure that flame propagation and other concerns are well understood and acceptable. A full-scale mockup for Apollo flammability testing is depicted in figure 1b.

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CHAPTER 4

Nonmetallic Materials for Improved Fire Safety

Extensive developmental effort for safe nonmetallic materials in spacecraft suggests many potential commercial, industrial, military, institutional, and domestic applications for these materials. Knitted and woven fabrics, webbings, cords, tapes, foams, potting compounds, wire insulation, adhesives, coatings, plastics, lubricants, sealants, molded items, laminates, and films are materials being considered. This report discusses only the textiles and elastomers. Suggested applications for some of these materials are summarized in table 4.

The flammability of a nonmetallic material is a function of the material thickness, its chemical composition, the curing process, the atmosphere in which the material is used, and other variables. For this reason, it is not possible to give complete flammability characteristics of all the materials discussed herein. Table 5 has been prepared, however, to summarize the flammability characteristics of some of these materials under specified Apollo spacecraft conditions. The information in this chapter was derived largely from the papers of D. G. Sauers of MSC.

TEXTILES

Textiles are used extensively for garments, carpeting, upholstery, bedding, and other uses, and may consist of natural or man-made fibers, either organic or inorganic. Natural fibers include cotton, jute, flax, ramie, hemp, abaca, sisal, wool, silk, and asbestos. The man-made organic fibers include rayon, nylon, Teflon, polyester, acrylic, vinyon, Saran, and polypropylene. The man-made inorganic fibers include glass and metals.

Some of the natural and man-made fibers were used in the Apollo spacecraft, with or without modification. With the exception of cotton, which is used in the astronaut undergarments, natural fibers could not be used in the extremely hazardous atmosphere of the spacecraft. Similarly, many of the man-made fibers were extremely flammable in the oxygen-rich atmosphere and could not be used. The fibrous materials used in the spacecraft consist of Beta fiber glass, polybenzimidazole, and Teflon. Other fibrous materials are used in ground operations, and include Nomex and asbestos.

Beta Fiber Glass

Textile fabrics of glass fibers are fire-resistant, and have been in use for several years as draperies and decorative hangings in homes, theaters, and hospitals, for example. The use of glass fabrics for garments, upholstery fabrics, and other applications has been impractical, because the fabrics have very low resistance to abrasion, and are too stiff to be comfortable.

The Owens-Corning Fiberglas Corp. developed a glass fiber called Beta fiber, which is much finer than the conventional fiber, and consequently, is much more flexible and comfortable. The development of this new fiber permitted the fabrication of fire-resistant garments that can be worn comfortably. Abrasion resistance was greatly improved by coating the Beta yarn with Teflon before weaving.

Some applications envisioned for Beta fabric when the surface durability problem has been solved are protective work clothing such as military flight coveralls, fuel and ammunition handlers' garments, fire-fighters' clothing, flameproof bedding for hospitals, hotels, and institutions, textile materials for wall coverings, and upholstery and floor coverings for public transportation equipment. Beta can also be used as a protective covering for materials used in the home.

TABLE 4.—*Suggested Applications for Nonmetallic Materials*

Application area	Fibrous materials	Elastomers	Other materials
Aviation	Seats Curtains Blankets Insulation Seat belts	Cushioning Headlining Walls Sunshades Pillows Window seals Conformal coatings Paint Oxygen hoses Oxygen masks Adhesives Carpeting	Plastics Windows Instrument faces Electroluminescent panels Wire insulation Heat-shrinkable sleeving Foams Intumescent coatings Structural composites Air-distribution systems Fire walls Antenna systems Nacelles Decorative panels Overhead racks Printed circuit boards
Automotive Cars Buses Trucks Ambulances	Seats Carpets Seat belts	Cushioning Coatings (fabrics) Headlining Side panels Foams Conformal coatings	Plastics Wire insulation Heat-shrinkable sleeving Intumescent coatings Structural composites Fire walls Air ducts
Marine	Upholstery fabrics Drapes Carpets Mattress covers	Foam (pillows) Foam (cushioning) Walls/ceilings Mattress protectors	Structural composites Vent ducting Crew-quarter structures Pleasure craft
Building construction	Insulation Roofing materials	Laminated panels Wallboard covering Siding Ceiling tiles Paints Adhesives Roofing materials	Plastics Wire insulation Intumescent coatings Structural composites Fire doors Paper Decorative panels/tiles Wallpaper
Furniture	Upholstery fabrics Webbing Ticking	Foam (cushioning) Coatings (fabrics)	
Packaging		Foam (packaging)	Paper Packaging materials Wrapping paper Structural composites Containers
Mobile motor home	Seats Carpets Bedding Seat belts	Cushioning Coatings (fabrics) Ceilings Walls Conformal coatings	Plastics Wire insulation Heat-shrinkable sleeving Intumescent coatings

TABLE 4.–*Suggested Applications for Nonmetallic Materials*–Concluded

Application area	Fibrous materials	Elastomers	Other materials
Garment	Fire-fighting clothing Racing coveralls Medical garments	Coatings	
Bedding	Blankets Quilts Bed spreads Mattress covers Pillow slips	Foam (mattresses) Foam (pillows) Mattress protectors	
Food service	Furniture fabrics Draperies Carpets Venetian blind tapes	Foam (cushioning) Coatings (fabrics) Walls/ceilings Carpet pads Sunshades Paints	Paper Menus Wallpaper
Hotel/motel	Mattress covers Upholstery fabrics Draperies Carpets Blankets	Foam (mattresses) Foam (pillows) Coatings (fabrics) Sunshades	
Electrical and electronic	Speaker grilles	Conformal coatings Adhesives (cabinets)	Plastics Intumescent coatings
Institutional Hospitals Clinics Nursing homes Schools	Draperies Blankets Mattress covers Carpets Upholstery fabrics	Foam (mattresses) Foam (pillows) Walls/ceilings Sunshades Coatings (fabrics) Hoses, anesthesia Hoses, oxygen Masks, oxygen Mattress protectors	
Commercial Department stores Specialty shops Banks Theaters Auditoriums Office buildings	Carpets Draperies Upholstery fabrics	Carpet pads Coatings (fabrics) Foam (cushioning) Walls/ceilings	
Domestic Homes Apartments	Bedding Carpets Draperies Upholstery fabrics Ironing board covers	Foam (upholstery) Carpet pads Coated fabrics	
Military	Protection for ammo boxes Protection for stored bombs Protection for fuels Flight garments	Wet suits in oxygen-rich decompression chambers	Plastics Intumescent coatings Paper Log books Flight manuals Maps Charts

TABLE 5.–*Flammability of Commercial Textile and Elastomeric Materials Tested in Oxygen-Rich Atmospheres*

Materials	Combustion Rate in./sec									
	Top ignition[a]				Bottom ignition[a]					
	Gage[b]	6.2[c]	Gage	16.5[c]	Gage	6.2[c]	Gage	16.5[c]	Gage	16.5[d]
Textiles										
Beta glass fabric, 4190B	.007	NI[e]	.007	NI	.008	NI	.008	NI	.008	NI
Beta glass fabric, 4484/Teflon					.008	NI	.008	NI	.008	NI
Polybenzimidazole, natural	.007	0.16	.007	0.20	.007	0.30	.007	0.41	.007	0.35
Teflon, T-8-42, TFE	.007	SE[f]	.007	SE	.007	0.30	.007	0.55	.007	0.30
Nomex, HT-18-45	.007	0.16	.007	0.33	.007	0.60	.007	1.00	.007	0.60
Durette, X-400					.012	0.31	.012	0.81	.012	NDA[g]
Durette, X-410	.007	0.31	.007	0.41	.007	0.41	.007	1.00	.007	0.55
Durette, X-420					.013	0.30	.013	NDA	.013	NDA
Asbeston	.012	SE	.012	SE	.012	SE	.012	SE	.012	SE
Elastomers										
Viton, VS-20001	.063	SE	.063	SE	.063	SE	.063	SE	.063	SE
Fluorel, L-3203-6	.063	SE	.063	SE	.063	SE	.063	SE	.063	SE
RTV[h] silicones										
SG12	.075	.017								
SG12D	.075	.015								
SG12F1 w/FTA-3	.075	SE								
SG12K1	.075	.013								
SG12K1C	.075	.008								
SG12K1C w/FTA-3	.075	SE								

[a]Silicone-rubber ignitor.
[b]Sample thickness, in.
[c]Test pressure, psia, 100 percent oxygen.
[d]Test pressure, psia, 60/40 oxygen-nitrogen.
[e]NI, no ignition.
[f]SE, self-extinguished.
[g]NDA, no data available.
[h]RTV, room-temperature vulcanizing.

Polybenzimidazole

PBI, as it is commonly called, is an aromatic polyimide fiber which was developed by the Celanese Corp. for the U.S. Air Force. The fiber has excellent abrasion resistance, and retains about 75 percent of its strength at 725° F. The principal use of PBI is for webbing, tapes, and cords, where flexibility and resistance to abrasion are the principal requirements. An example of a PBI application is shown in figure 19.

Teflon

Teflon is a fluorocarbon (organic) material that has excellent chemical resistance, good wear qualities, and low coefficient of friction. There are two types of Teflon materials: Polytetrafluoroethylene (TFE), and fluorinated ethylene-propylene (FEP). TFE is a straight chain structure of carbon and fluorine that begins to sublime into a gas above 620° F. FEP is a branched chain chemical structure that becomes a fluid above 500° F.

In the Apollo spacecraft, Teflon was used as (1) a coating for Beta fibers to reduce fiber friction, (2) a fabric for coveralls (fig. 20), (3) a film to wrap electric wire harnesses, and (4) insulation for electric wires.

Nomex

A member of the nylon family of fibers, Nomex was developed by E. I. DuPont de Nemours and Co. for good dimensional stability and heat resistance.

FIGURE 19.–Personal restraint harness made of polybenzimidazole. (The fire and abrasion resistance of this material makes it suitable for this application.)

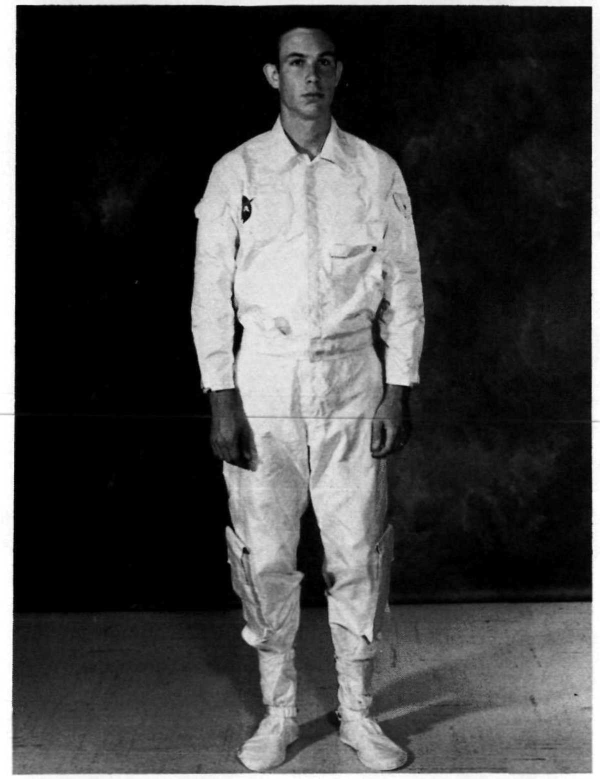

FIGURE 20.–Typical application for Teflon fabric. (This garment is worn by the Apollo astronauts inside the spacecraft; it is made of bleached Teflon.)

Nomex is used for such things as electric insulation, gas filter bags, ironing board covers, tires, coveralls, pajamas, upholstery, and children's clothing. It is available in yarn, staple or tow fiber, and paper. Its abrasion resistance is superior to cotton, wool, or acrylic fibers. A fire-protective garment is shown in figure 21.

Durette

Durette X-400 is a modified aromatic polyamide fiber, manufactured by the Monsanto Co., that is nonflammable in air, but burns in oxygen-rich atmospheres. The material was made fire-resistant by coating with Fluorel. Durette has been used to refurbish the interior of NASA aircraft, and to make jackets, trousers, boots, and gloves for the crew of the Skylab missions. The material has also been used for firemen's suits and helmets.

Asbeston

Asbeston is an asbestos fabric, developed by the Uniroyal Co., that consists of asbestos fibers and Beta fibers. The fabric has excellent heat resistance and good flexibility.

ELASTOMERS

Elastomers are natural and man-made rubber-like materials with a high degree of resiliency or elasticity. They are used in extruded or molded items, in potting compounds, and as fabric and conformal coatings, sealants, adhesives, films, and foams.

Examples of elastomers are butyl rubber, urethane, the silicones, and polysulfides. Urethane is commonly found in pillows, mattresses, and upholstered furniture. The silicones are often used as seals on refrigerator and food freezer doors; the polysulfides are commonly used as sealants and caulking compounds.

Fluorocarbon Polymers

These materials are used extensively in the Apollo spacecraft and other applications, and have potential for commercial use. New compounds of Fluorel, a Minnesota Mining and Manufacturing (3M) Co. development, and Viton, developed by E. I. DuPont de Nemours and Co., may be cast, molded, and

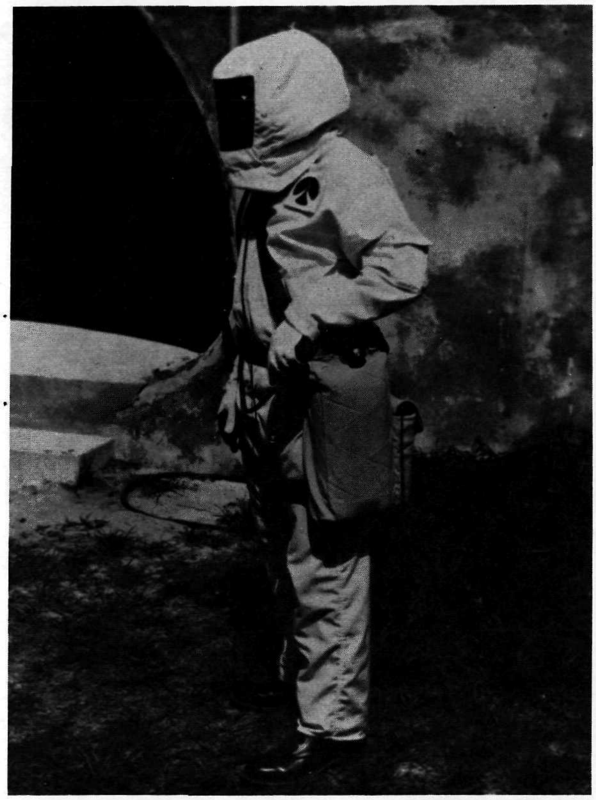

FIGURE 21.–A fire-protective garment made of Nomex.

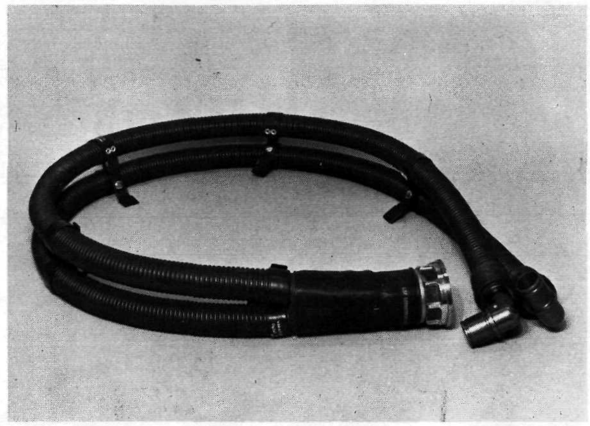

FIGURE 22.–Oxygen hose–an example of fluorocarbon elastomer molded products.

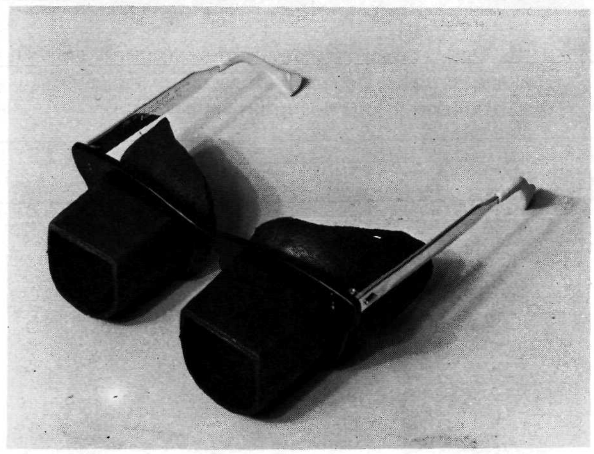

FIGURE 23.–Foam eyepieces–an example of fluorocarbon elastomer castings.

extruded. Figure 22 shows an oxygen hose which was molded, and figure 23 is an example of an item that was cast. The compound is also used extensively as a protective coating, in paste or sprayable form. Under atmospheric conditions, a 3-mil coating of 100 percent fluorocarbon will flameproof ordinary paper exposed to a propane torch flame.

The solution can be used with a room-temperature cure, and passes the most stringent flammability tests. The pure solution can be used with various additives. Inorganic pigments can be used for coloring, but must be limited to less than 5 percent by weight to preserve the elongation properties of the film.

Asbestos has been used as an additive to improve thermal insulation characteristics. It can be added to plastics in any quantity up to 50 percent by weight, at which point the cured mixture becomes brittle. A mixture containing 75 percent fluorocarbon and 25 percent asbestos provides the best flexibility and flammability characteristics. The asbestos additive renders the coating gas permeable, but this can be overcome by using pure fluorocarbon as an impermeable subcoat or overcoat.

Potting, Encapsulating, and Coating Compounds

These materials are used for insulation, environmental protection, and mechanical support of electric system elements such as connectors, printed circuit boards, and terminal boards. Conventional compounds are epoxy, silicone, and polyurethane based compounds, all of which are flammable in oxygen-rich atmospheres. Several classes of materials were investigated under an MSC program to develop a potting and encapsulating compound which would be nonflammable in oxygen-rich atmospheres, including

room-temperature vulcanizing (RTV) silicones and fluorosilicones, ceramics, fluorocarbons, and brominated polyesters.

1. RTV silicones.—Five formulations of this class of materials were developed at MSC; all exhibit good flame resistance in oxygen-rich atmospheres. They must be overcoated with a fluorocarbon coating (such as Emerson and Cuming, Inc., FTA-3) to reduce moisture transmission, and to further enhance the flammability characteristics of the installation.

2. RTV fluorosilicones.—Several formulations of this class of materials were developed by Furane Plastics, Inc.; all exhibit good flame resistance in 60/40 oxygen-nitrogen atmospheres.

3. Fluorocarbon compounds.—Several formulations were tested by Emerson and Cuming, Inc., using 3M Fluorel, or DuPont Viton, with asbestos fibers and Eccospheres (glass microballoons) as the principal fillers. Of these formulations, one was selected as the best compromise (Formulation 1015). This compound is porous, and must be sealed with the Emerson and Cuming FTA-3 compound or an equivalent to keep out moisture.

4. Ceramic compositions.—Where flexibility of the potting material is not a constraint, the Emerson and Cuming Formulation QC-15 can be used. This compound consists of asbestos fiber, glass microballoons, silica, and anhydrous sodium silicate. The resulting material is porous, and must be sealed to exclude moisture.

5. Brominated polyester.—Another Emerson and Cuming material which has good fire-retardant properties is the MRTA-5 conformal coating. This formulation contains no volatile solvents, and can be applied by brush, spray, and dip techniques. The compound cures in 6 to 8 hr at room temperature.

Glossary

Ablation–Sublimation, vaporization, or melting of a surface material due to heating resulting from a fluid moving past it at high speed. This phenomenon is often used to protect a structure from overheating by providing an expendable ablation surface, such as the heat shield on a re-entry vehicle or a protective coating in a combustion chamber.

Acrylic–A generic name for a manufactured fiber in which the fiber-forming substance is any long-chain synthetic polymer composed at least 85 percent by weight of acrylonitrile units.

Brominated polyester–A polyester with bromine added. (See polyester)

Conformal coating–A material applied over another material for protection.

Copolymer–A synthetic substance formed by the addition or condensation polymerization of two or more monomers.

Dielectric–Electrically nonconducting.

Dysbarism–A disease that results principally from the formation of gas bubbles in the body tissues and fluids as a consequence of exposure to a decrease in barometric pressure from an initial pressure of one atmosphere. Often called decompression sickness, bends, or chokes.

Elastomer–A material which at room temperature can be stretched repeatedly to at least twice its original length and, upon immediate release of the stress, will return with force to its approximate original length.

Firepoint–The fire (ignition) point is the lowest temperature at which a heated material will emit sufficient flammable vapors to result in a self-sustaining fire when the vapors are mixed with oxygen and exposed to an electric spark of a preselected energy level (usually 100 mJ at 10,000 V).

Fireproof–Noncombustible.

Fire retardant–Slowly combustible.

Fire resistant–With respect to sheet or structural members, the capacity to withstand heat without igniting at least as well as aluminum alloy in dimensions appropriate for the purpose for which they are used; with respect to fluid-carrying lines, other flammable fluid system parts, wiring, air ducts, fittings, and power plant controls, the capacity to perform the intended functions under the heat and other conditions likely to occur at the place concerned.

Fire safety–Low probability of serious loss or injury by fire (combustion).

Flame resistant–Not susceptible to combustion to the point of propagating a flame after the ignition source is removed.

Flammable–With respect to a fluid or gas, susceptible to igniting readily or to exploding.

Flammability–The propensity of a material to burn.

Flashpoint–The lowest temperature at which a heated material will emit flammable vapors in such quantities that these vapors will result in a nonsustaining flash or flame when mixed with oxygen and exposed to an electric spark of a preselected energy level (usually 100 mJ at 10,000 V).

Flash resistant–Not susceptible to burning violently when ignited.

Fluorosilicone–A silicone resin in which hydrogen atoms have been replaced by fluorine.

Hyperbaric–Pressures greater than sea level pressure.

Hypobaric–Pressures less than sea level pressure.

Intumescence–The property of certain special plastics to swell on application of heat.

Mockup–A full-sized structural model built accurately to scale chiefly for study, testing, or display.

Offgassing–The evolution of gaseous products from a liquid or solid material.

Organic compounds–Nonpolar compounds that generally consist of carbon and hydrogen with or without oxygen, nitrogen, or other elements, except those in which carbon plays no important part, for example, carbonates.

Oxygen-rich (oxygen-enriched)–A gas mixture containing more than the amount of oxygen normally found in air.

Polybenzimidazole (PBI)–A high-temperature-resistant polymeric fiber containing characteristic imide groups.

Polycarbonate–A transparent plastic used for helmet visors. It has exceptionally high impact strength.

Polyester–A generic name for a manufactured plastic which is any long-chain synthetic polymer composed of a polyhydric alcohol and a hydroxy acid.

Polymer–A compound formed by the reaction of simple monomers having functional groups that permit their chemical combination to proceed to high molecular weights under suitable conditions. Polymers may be formed by addition or condensation. When two or more monomers are involved, the product is called a copolymer.

Polyquinoxaline–A high-temperature thermosetting resin derived from quinoline by the substitution of a nitrogen atom for a methylidine group.

Polysulfone–A high-temperature polymer characterized by the sulfonyl group doubly united by means of its sulfur, usually with carbon.

Polyurethane–Any of the various polymers produced by polymerization of a hydroxyl (OH) radical and an NCO group from two different compounds.

Pyrolysis–Decomposition of a material at elevated temperature without flame or heat.

Silicone–Any of a group of synthetic resins, oils, greases, and plastics, in which the carbon has been replaced by silicon.

Thermal conductivity–The amount of heat that passes, in unit time, through a unit volume (1 cm^3) of a substance when the opposite faces of the cube differ by 1° C.

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